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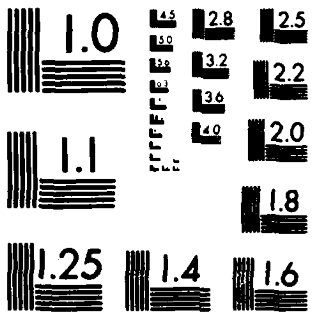
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SECOND CONFERENCE ON SEMI-INSULATING III-V MATERIALS

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28 February 1983

UNITED STATES OF AMERICA

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The Second Conference on Semi-insulating III-V Materials dealt with four main issues: growth of bulk III-V crystals, assessment of high resistivity materials, behavior of high resistivity materials under heat treatments, and problems of III-V devices related to the semi-insulating conditions.

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SECOND CONFERENCE ON SEMI-INSULATING III-V MATERIALS

The Second Conference on Semi-Insulating III-V Materials was held from 19 to 21 April 1982 in Evian, France. (The first conference took place in Nottingham, England, in 1980). The author found both conferences to be among the most stimulating and informative he has attended. The size of the conference (about 160 participants), the absence of parallel sessions, and the focused topic all contributed to the effectiveness.

While 13 countries, including the People's Republic of China, were represented, participants from France (58), Great Britain (36), and the US (25) accounted for 75% of the attendance. The organizers selected 42 papers for oral presentation, and 16 were presented as posters. All manuscripts to be published in the proceedings were refereed before the meeting, and authors were expected to provide revised manuscripts at the time of the conference.

Oral presentation sessions and poster sessions were devoted to the topics of growth of bulk III-V crystals, assessment of high resistivity materials, and behavior of high resistivity materials under heat treatment. One session treated semi-insulating conditions as problems of III-V devices. In the author's view, the conference followed three general trends: a preoccupation with the identification and control of the main electron trap in GaAs (EL2), somewhat less emphasis on InP than at the Nottingham Conference, and less emphasis on chromium (Cr)-doped GaAs. The third trend was typified by an evening rump session entitled "Cr in GaAs is Dead."

Growth Technology

The session on growth of III-V crystals began with an invited paper by G. Jacob (Laboratoire d'Electronique de Physique [LEP], France), who discussed techniques for the reduction of defect densities introduced during LEC growth of GaAs and InP. The study of small diameter crystals (<15 mm) that have been grown dislocation free and theoretical calculations of thermal gradients and related stresses have permitted determination of the critical resolved shear stress (CRSS) above which dislocations are generated. The CRSS depends strongly upon the stoichiometry of the crystal, the behavior of native point defects, and the interaction between native defects and impurities at temperatures just below melting point. Reductions in dislocation density can be achieved by decreasing thermal stresses during growth (e.g., by using a new growth method called Liquid Encapsulated Kyropoulos), or by increasing the CRSS through doping with donor impurities or isoelectronic species that reduce the concentration of mobile native defects through complex formation. Jacob predicted that dislocation-free GaAs and InP soon will be used exclusively.

One of the major developments in GaAs growth technology during the past year was the demonstration that the electrical compensation of undoped GaAs is controlled by melt stoichiometry. D.E. Holmes (Rockwell, US) discussed the observation that the concentration of the deep donor EL2 in LEC GaAs depends on the As concentration in the melt, increasing from $5\times10^{15}cm^{-3}$ to $1.7\times10^{16}cm^{-3}$ as the As atom fraction increases from 0.48 to 0.51. Semi-insulating material

can be obtained only above a critical As melt composition for which the concentration of the deep donor EL2 is sufficient to compensate residual shallow acceptors. It was pointed out that the results are consistent with the identification of EL2 with a native defect such as the anion defect (As_{Ga}) that was observed previously in GaAs by electron paramagnetic resonance (EPR) techniques. Holmes discussed the characterization of the GaAs samples by a variety of optical and electrical techniques, including the measurement of the lateral inhomogeneity of the concentration of EL2 across a wafer. The EL2 density described a "W"-shaped curve across the wafer that showed no correlation with the etch pit density. The W was explained in terms of two vortices that form in the flow pattern of the molten GaAs. In addition to the EL2 studies, Holmes reported the observation of an acceptor with 77-meV binding energy that was attributed to the GaAs antisite defect. The acceptor was reported in several other papers at the conference for p-type Ga-rich-grown GaAs; its dependence on melt stoichiometry is the only basis for the Ga_{As} hypothesis.

H.M. Hobgood (Westinghouse, US) presented a related paper that also established the relationship between melt stoichiometry and the EL2 concentration in LEC-grown GaAs and reported the ∿79-meV acceptor. In addition, he discussed surface conversion of GaAs during annealing and the influence of EL2 out-diffusion. Hobgood also touched on the topic of residual boron impurities in undoped GaAs, a topic that was treated in detail in a paper by K. Tada and co-workers (Sumitomo, Japan) on boron-doped semi-insulating LEC GaAs. The workers have succeeded in doping with boron at concentrations higher than $10^{18} cm^{-3}$. They found that the doping level depends on boron concentration in the melt and the H_2O content of the B_2O_3 encapsulant. Unintentional boron levels in undoped GaAs are $\sim 10^{15}$ to $10^{16} cm^{-3}$.

Other topics included automated mapping of dislocation densities using a scanning vidicon with digitized output by M. Bonnet (Thomas CSF, France), the growth of Fe-doped and "undoped" semi-insulating InP by Sun Tongnien (Hebei Semiconductor Research Institute, People's Republic of China), and a comprehensive study of 50 species of chemical impurities in 40 ingots of undoped LEC GaAs presented by J.P. Farges (LEP, France). Farges reported that the improved control over the comparative ratio of shallow and deep impurities made possible by this detailed study had increased the yield in the production of undoped semi-insulating GaAs from 40 to 80%.

High Resistivity Materials

An invited paper on chemical characterization of semi-insulating bulk GaAs and InP by J.B. Clegg (Philips Research Labs., UK) opened the first of two sessions concerning assessment of high resistivity materials. Clegg briefly surveyed a range of chemical characterization techniques and their application to the detection of impurities in III-V semiconductors. The techniques discussed included flameless atomic absorption spectroscopy (FAAS), spark source mass spectroscopy (SSMS), secon-

dary ion mass spectroscopy (SIMS), neutron activation analysis (NAA), and local vibrational mode infrared spectroscopy (LVM). While the range of instrumental techniques available has remained essentially unchanged during the last decade, considerable progress has been made in element detection sensitivity, precision, accuracy, and spatial resolution. New levels of confidence in analytical results have been established by intercomparison of techniques and a wider use of standard or reference samples.

I. Grant (Cambridge Instruments, UK) described the use of ^{51}Cr as a radio tracer element to determine the distribution of Cr in LEC-grown crystals of semi-insulating Cr-doped GaAs. The distribution of Cr exhibited good uniformity across wafers; however, the segregation coefficient appeared to vary along the length of the crystal. In addition, etch pit density and resistivity were mapped for comparison with the Cr distribution. The etch pit density seemed to be independent of the Cr distribution. The "M"-shaped (inverted W) radial distribution curve reported by Holmes and others reappeared in the resistivity maps along the (110) diameter for wafers of undoped GaAs, with maxima occurring in the resistivity at half radii.

The paper was typical of several reports at the conference on the mapping of spatial distributions of etch pit density, resistivity, EL2 concentration, etc. Considerable ingenuity is being applied in the development of such mapping techniques. For example, R.T. Blunt (Plessey, UK) reported on the application of a novel nondestructive technique for the mapping of electrical uniformity in semi-insulating substrates. In this "dark spot" method, a scanning dark spot is used to interrupt an illuminated line or sheet extending across the semi-insulating wafer. This places a short segment of high resistivity (unilluminated) material in series with the low resistivity photoconducting channel, thereby providing localized measurement of the dark resistivity at the location of the dark spot. Resistivity maps were obtained for a variety of Cr-doped and undoped Bridgman and LEC-grown GaAs crystals. Again, the "W"-shaped curves were observed for maps of resistivity along the wafer diameter. Considerable changes in wafer uniformity patterns were found as a function of position along the ingot.

Related papers on the characterization of Co-doped InP were presented by M.S. Skolnick (Royal Signals and Radar Establishment [RSRE], UK) and K.R. Duncan (Nottingham Univ., UK). Heavy Co doping of LEC InP produces semi-insulating material ($\sim 10^7$ ohm-cm). Skolnick reported deep level transient spectroscopy (DLTS) and photocapacitance measurements in lightly doped n-type InP:Cothat enabled detection of a deep electron trap with a thermal emission activation energy of 0.53 eV (E_c-0.53 eV). This is interpreted as the deep acceptor level due to substitutional Co on the In site. The observed resistivity in highly doped semi-insulating InP:Co is rather high for an E_c-0.53 eV level. The apparent discrepancy is attributed to the relatively low carrier mobility, which is an order of magnitude lower than that observed in InP:Fe. The photoluminescence (PL), photoluminescence excitation (PLE), and optical absorption spectra are interpreted as transitions between the $^4A_2$, $^4T_2$, and $^4T_1$ crystal

field levels of the $Co^{2+}(d^7)$ ion on the In site. The E_c-0.5 eV level is identified with the $Co^{2+} \rightarrow Co^{3+} + e^-$ transition. A second deep level that was also believed to be Co-related was found at E_v+0.3 eV by DLTS and photocapacitance techniques.

Duncan described photoconductivity measurements on n-type and semi-insulating InP:Co. A strong photoconductive onset at 1.13 eV (4.2K) in semi-insulating material is interpreted as electron excitation into the conduction band from the $Co^{3+}(d^6)$ neutral site of Co on the In site. The photoconductive responses of both n-type and semi-insulating material show a series of sharp structures in the 0.78- to 0.85- eV range that correspond to the internal state transitions out of the $^4A_2$ ground state of the Co^{2+} acceptor level, indicating that the final states of the transitions are degenerate with the conduction band.

It is inferred from the above experimental results that the behavior of Co_{In} in InP is qualitatively consistent with the properties of other transition metal impurities in InP--such as Mn and Fe. However, the ionization energy of Co^{2+} is surprisingly small by comparison with the corresponding energies for Co in GaAs (1.36 eV) and GaP (1.95 eV). This may be a manifestation of the departure from the expected trends in transition metal energy levels as the localized transition metal d-levels approach the valence band edge with increasing atomic number in the sequence Mn, Fe, Co, Ni, etc.

GaAs:Cr--Is It Dead?

The evening rump session titled "Cr in GaAs is dead" was organized and introduced by P.R. Jay (Thompson CSF, France). Jay presented a brief review of the rise to prominence of GaAs:Cr and its recent fall from grace due largely to the success of undoped S.I. GaAs and problems with Cr redistribution during processing at elevated temperatures. His review was entertainingly introduced with a "birth certificate" for GaAs:Cr and ended with the corresponding "death certificate." Some of the subsequent speakers in the session felt that the reports of the death of GaAs:Cr are, to paraphase Mark Twain, greatly exaggerated. However, this was not the case for the first speaker, D.E. Holmes (Rockwell, US), who expressed the belief that GaAs:Cr is certainly not the material of choice for the ion-implantation-based GaAs IC technology, but that undoped Si GaAs is far superior. In contrast, K. Fujita (Sumitomo, Japan) pointed out that in Japan alone about 3 tons of chromium doped GaAs crystals were pulled during the past year. Sumitomo also believes that the horizontal Bridgman growth technique is alive and well, and 3-in.-diameter round wafers of GaAs:Cr have been produced by the technique. Fujita indicated that the best material might incorporate a combination of low Cr doping and EL2. However R.M. Ware (Cambridge Instruments, UK) asserted that a "snifter of Cr is useless," and that more than 1 ppm Cr is needed to have any useful effect in the production of SI GaAs. M. Cardwell (Plessey, UK) presented a comparative study of performance parameters for GaAs microwave devices fabricated on undoped GaAs substrates and Cr-doped GaAs sub-

strates. The results showed no statistically significant differences between performance levels obtained with the two substrate materials.

A widely ranging discussion followed; it touched on the variation of impurity levels with suppliers of Ga and As starting materials, the persistence of C as a residual impurity in LEC growth and Si as a residual in Bridgman growth, and (once again) the identification of EL2--is it the As_{Ga} antisite or possibly an As-Frenkel defect as suggested by T.J. Hurle (RSRE)? The final comment of the evening from the audience held that the discussion had been misguided. The three most important factors concerning GaAs device production were "yield, yield, and yield," and why hadn't the conference concerned itself with such considerations? Such sentiments were echoed the following evening by the conference banquet speaker, J.L. Teszner (Director Recherche Etudes Techniques [DRET], France), who exhorted the participants to pay less attention to fundamentals and get on with the development of the III-V technology. However, most participants felt that the admonitions were unjustified.

Assessment of High Resistivity Materials

The second session on assessment of high resistivity materials opened with an excellent invited review paper on the role of point defects in GaAs by J. Schneider (Institut für Angewandte Feströrperphysik [IAF], Freiburg, FRG). He began by pointing out that point defects can play a role in devices through compensation (deep levels), nonradiative recombination, and Fermi level pinning in Schottky contacts. The catalog of defects includes vacancies, interstitials, antisite defects, and possible defects and possible associates such as divacancies, close Frenkel pairs (V_{Ga}-$Ga_{interst.}$, V_{As}-$As_{interst.}$), and the "antistructure pair" As_{Ga}-Ga_{As}. As vacancies and interstitials are known to be mobile at $T > 200°C$, their occurrence as isolated defects in as-grown material is relatively unlikely. However, the isolated defects can be produced by electron irradiation. For example, electron irradiation produced the E1-E5 family of electron traps in GaAs that were studied by DLTS in the mid-1970s. Unlike the II-VI's, in which the electron spin resonance (ESR) of various defects has been studied extensively, until recently there have been no ESR observations of native defects in GaAs. Schneider then reviewed the recent ESR studies of the As antisite in GaAs, its first observation at a concentration of $\sim 10^{15} cm^{-3}$ in as-grown material by Wagner et al., and the enhancement of its concentration by neutron and electron irradiation as well as plastic deformation. Again the possible connection with the electron trap EL2 was discussed, including the recent photosensitivity of ESR measurements of Weber et al. (1982), which may establish an optical metastability for the As_{Ga} ESR spectrum similar to that exhibited by the EL2 capacitance transient signature. Schneider also discussed neutron transmutation doping of GaAs and pointed out that in addition to the transmutations Ga → Ge and As → Se, β and γ recoils generated by thermal neutrons can create As_{Ga} antisite defects.

The theme of EL2 in GaAs and its possible association with the

As antisite was continued in a paper presented by J. Lagowski (MIT). The concentration of EL2 in horizontal Bridgman grown GaAs was found to be a function of the As pressure during growth, the concentration of shallow donors (acceptors), and the partial pressure of Ga_2O in the growth ampoule. The observations were explained by attributing EL2 to the As antisite defect that is formed as a result of the migration of Ga vacancies during the post-growth cooling of crystals:

$$V_{Ga}^{-} + As_{As} \rightleftarrows As_{Ga}^{++} + V_{As}^{+} + 4e^{-}.$$

The interaction involves a large change in electric charge and could be controlled by electron concentration, thus the dependence upon shallow donor concentration. It was suggested that the influence of oxygen on the deep level concentration results from the reduction of Si donor concentration by oxygen rather than direct electrical activity of the oxygen.

Two closely related papers concerned photoluminescence (PL) and PL excitation (PLE) studies of a broad PL band in GaAs near 0.62 to 0.65 eV that has recently been attributed to the EL2 center. S.G. Bishop (NRL, US) discussed PLE spectra of the 0.635 eV PL band that exhibited a strong extrinsic peak involving below-gap absorption due to ionized shallow acceptors. From the data it was inferred that the broad PL band could involve donor-acceptor pair recombination between electrons in the EL2 level and holes trapped at neutral shallow acceptors. A second broad PL band at 0.68 eV was ascribed to EL2 to valence-band transitions. P. Leyral (Institut National des Sciences Appliquées, France) discussed similar PLE spectra and the fatigue or quenching effect for the ~0.64 eV PL band that is the strongest evidence for the association of this PL band with EL2. He also established a strong similarity between the onset and line shape of the broad extrinsic PLE for the band and the photoionization spectrum, σ_n^o of the EL2 level. He interpreted the data as being consistent with conduction-band to EL2 transitions for the ~0.64 eV PL band.

The session then turned to the topic of chromium-doped GaAs. J.S. Blakemore (Oregon Graduate Center, US) discussed electronic distributions over the Cr^{2+}, Cr^{3+}, and Cr^{4+} charge states of Cr_{Ga}, and, in particular, the optical generation of Cr^{4+} in SI GaAs. Extrinsic IR photoconductivity and photo-Hall spectra determined a 0.45-eV threshold for optical pumping of holes from Cr^{4+}. B. Cavenett (Univ. of Hull, UK) reported optically detected magnetic resonance (ODMR) studies of GaAs:Cr that comprise the first observation of spin-dependent charge transfer processes in III-V semiconductors. He discussed ODMR studies of the 0.835-eV emission band, which is due to an internal transition of an axial (Cr^{2+}-x) center. ODMR signals from this emission show [111] symmetry and have been assigned to a (Cr^{3+}-x) center. The signal depends on the spin pumping of the conduction band electrons and shows that the charge transfer process

$$(Cr^{3+}\text{-x}) + e_{CB} + (Cr^{2+}\text{-x})^{*}$$

is spin dependent. The ODMR of Cr^{4+} shows that a competing hole transfer process is observed. On excitation

$$Cr^{3+} + h \rightarrow Cr^{4+} ,$$

followed by the de-excitation process

$$(Cr^{2+}-x)^{*} + Cr^{4+} \rightarrow$$

$$(Cr^{3+}-x) + Cr^{3+}.$$

After a paper on mixed photoconductivity in SI GaAs:Cr by O. Ogawa (Université des Sciences et Techniques du Languedoc, France) and one concerning phonon studies of GaAs:Cr by P.J. King (Univ. of Nottingham, UK), the session ended with an invited paper on the future of integrated opto-electronics by J.P. Noblanc (Centre National d'Etudes des Telecommunications [CNET], France). Noblanc discussed efforts to realize monolithically integrated opto-electronic circuits that allow the association on a single substrate of electrical devices such as transistors, with optical devices such as lasers, photodetectors, and modulators. He reviewed the potential applications of III-V alloys such as GaAs-GaAℓAs and InP-GaInAsP, including some of the opto-electronic devices that have been fabricated successfully.

Behavior of High Resistivity Materials

The session on the behavior of high resistivity materials under heat treatments began with an invited paper by J. Kasahara (Sony Corp., Japan). His subject, the redistribution of implanted impurities in SI GaAs, served as an excellent introduction to a session in which nearly all papers dealt with the redistribution of impurities. Kasahara emphasized the importance of the ion implantation technology for the further development of GaAs ICs and FETs and pointed out that control of the redistribution of implantants during the post-implantation anneal underlies the viability of the technology. He listed four factors that control redistribution: (1) stoichiometry in the substrate during implantation and annealing, (2) radiation damage, (3) impurity concentration and concentration gradient, and (4) thermal stress during annealing. The factors are not independent but are closely correlated so that the redistribution of implanted impurities is complicated, particularly for high dose implantation.

The next paper scheduled by representatives of the Institute of Metallurgy, Shanghai, was not given because none of the authors was present. There followed two papers on Mn in GaAs. The first was an analysis of the anomalous out-diffusion of Mn in GaAs by A.S. Jordan (Bell Labsoratories, US). Jordan discussed a simple model combining chemical kinetics and interstitial-substitutional diffusion to explain the diffusion of background Mn to the surface of GaAs. Mn interstitials generated at the center of the slice diffuse to the surface where they are trapped by in-diffusing Ga vacancies. Predictions of the model were consistent with the Mn redistribution data of Klein et al. (J. Appl. Phys., 51, 4861 [1980]). A. Goldzene (Université Louis Pasteur, Strasbourg, France) presented an EPR assessment of Mn gettering in GaAs. The Mn^{2+} EPR was studied in co-doped GaAs:Mn:Cr samples to assess the Mn^{2+} content after applying the thermal conditions typical of processing steps. The work addressed the

controversial question of the source of the Mn that accumulates at the surface and is sometimes responsible for surface-type conversion. Is it introduced as a contaminant of the H_2 flow or other processing condition (e.g., furnace), or does it come from the bulk substrate? The data presented by Goldzene appeared to implicate a contaminant; however, ensuing discussion indicated that it is not possible to generalize. One must analyze each substrate and processing combination individually and apply all of the characterization tools available.

B. Deveaud (CNET) discussed a chromium-oxygen interaction in GaAs. For oxygen implanted into Cr-doped or undoped GaAs, depending upon the implantation dose, the oxygen atoms either diffuse or are blocked in the implantation region and pile up during annealing. When they pile up, a Cr gettering occurs for Cr concentration greater than $10^{16} cm^{-3}$, and a chemical interaction between Cr and O is suggested. During annealing following dual implantation of O and Cr at different depths the Cr ions move toward the O-implanted zones. In some cases, the O implanted layer can be a good barrier against Cr diffusion. This is important, as the diffusion of Cr over a distance of 300 μm during a 20-min anneal at 900°C was demonstrated.

G.M. Martin (Laboratoire d'Electronique de Physique [LEP], France) continued the topic of O implantation into GaAs. He began by re-emphasizing the finding that the production of SI GaAs by the introduction of O relies on the gettering of Si shallow donors rather than the introduction of an oxygen-related deep level. Specifically, EL2 concentrations are unaltered by the introduction of oxygen. Oxygen implantation removes carriers through the formation of complexes associated with Si and Se. A much larger compensation is observed for Si doped materials; however, the only deep level detected so far (at E_c - 0.54 eV) is associated with a Se-O complex. Oxygen implantation also strongly lowers the exodiffusion rate for EL2 in bulk material annealed under an Si_3N_4 cap. This exodiffusion can lead to p-type surface conversion of undoped SI wafers.

A paper concerning the optical and thermal properties of deep levels related to Fe in GaAs and InP was presented by G. Guillot (Institut des Sciences Appliquées de Lyon, France). DLTS measurements confirmed earlier findings of deep acceptor levels at E_v + 0.55 eV in GaAs and at E_c - 0.63 eV in InP. Optical photoionization cross-sections for transitions between the levels and the conduction and valence bands were measured by the DLO technique. The results for σ_n^0 were interpreted as transitions from the Fe^{2+} (^5E) ground state to the different CB minima (Γ, L, X) and for σ_p^0 as transitions from the VB to the Fe^{2+} (^5E) ground state and the Fe^{2+} ($^5T_2$) excited state. PLE spectra for the Fe^{2+} PL bands in InP:Fe and GaAs:Fe were compared to the photoionization spectra and interpreted in parallel fashion. The VB to Fe^{2+}($^5T_2$) excited state extrinsic excitation mechanism

proposed previously by Bishop et al. at the Nottingham III-V conference was confirmed. For GaAs:Fe a weak feature ~0.3 eV above the threshold in the Fe^{2+} PLE was interpreted as transitions from the spin-orbit split off VB.

L. Eaves (Univ. of Nottingham, UK), after referring to InP as the "Cinderella material" of the conference, presented results of a PL study of SI InP:Fe, InP:Mn, and undoped and thermally annealed InP. After studies of more than 60 samples, it was concluded that the occurrence of two similar PL bands peaking at 1.10 eV with associated phonon structure and at 1.15 eV with phonon structure had led to much confusion in earlier work. It was found by studying doped samples that the 1.15-eV band is related to Mn and the 1.10-eV band to Fe. Studies of undoped crystals indicate that both Mn and Fe can be present as inadvertent impurities. In undoped samples, annealing strengthened the Mn PL band by factors ~40 and diminished strongly following a 20- to 30-μm surface etch, suggesting that the Mn diffuses to the surface during the anneal. Other bands observed included a 1.07-eV band that other workers have related to native defect complexes (with no firm evidence) and a 1.289-eV zero phonon line associated with Cu.

The session ended with a paper by F.J. Tegude on deep-level profiles of GaAs active layers and their correlation to substrate properties. Photocapacitance, photo-FET, and DLTS investigations of LPE grown active GaAs layers of SI GaAs substrates led to the conclusions that the main traps in the active layers are introduced from the substrates. A paper that was to have been given by representatives of Vilnius Univ. (USSR) was not presented because the authors did not attend.

III-V Devices and Semi-Insulating Conditions

The final session of the conference concerned problems of III-V devices related to semi-insulating conditions. C.P. Lee (Rockwell International, US) began with an invited paper in which he discussed the influence of substrates on the electrical properties of GaAs FET devices and integrated circuits. The semi-insulating substrate provides isolation between devices and minimizes parasitic capacitances. In devices that have low pinch-off voltage, such as those used in digital integrated circuits, device characteristics can be strongly influenced by the properties of the substrate, and problems such as nonuniformity, nonreproducibility, and degradation in performance can arise.

Lee discussed two effects, substrate orientation and backgating. The characteristics of ion-implanted MESFETs fabricated on (100) substrates depend on the orientation of the devices--that is, upon the orientation of the gate relative to the crystal axes of the substrate. For example, pinch-off voltages exhibited a pronounced dependence upon gate length (1 to 50 μm) for one of the [110] directions, (110), but not for the other, (011). The (011) orientation also had high transconductance. In addition, the statistical scatter-uniformity of pinch-off voltages for large numbers of devices was found to be a function of substrate orientation. Selection of the correct device orientation before wafer processing is important for the reproducibility, uniformity, and performance

of the devices. As the semi-insulating substrate is not an ideal intrinsic material and its semi-insulating character is achieved by a compensation mechanism, a p-n junction-like space-charge region exists at the conduction channel-substrate interface in the FET. Modulation of the space charge region by voltage applied to the substrate can influence device characteristics. The effect is called backgating, which tends to reduce pinch-off voltage and transconductance and contributes to the temperature and light sensitivity of device performance. The use of proton bombardment to produce a damaged layer for isolation between devices was discussed as one method for the control of backgating. A second method is the use of a partially p-type drain that injects holes to compensate electrons that cause backgating at the substrate-channel interface.

S. Makram-Ebeid (LEP, France) also discussed backgating effects in a paper on low frequency anomalies in GaAs MESFET structures. Two effects were examined, a nonlinear frequency-dependent transconductance effect between the substrate voltage and the drain current transients produced by an abrupt change of the drain voltage. The transients contain time constants that are substrate potential dependent. Space charge trap limited carrier injection occurs in the substrate that apparently depends upon the net concentration of deep levels at the channel interface. This indicates a need for closer compensation in the substrate.

There followed two papers presented by representatives of Thomson CSF, France. R.H. Wallis discussed a method for investigating the profile of the carrier mobility in the conducting channel of a GaAs MESFET. The method uses the magnetic field dependence of the transconductance to obtain the mobility profile directly on the MESFET without resorting to special test structures. The results indicated that the drop in mobility near the channel-substrate interface is not due to deep traps emanating from the substrate as has long been suspected, but that the reduced mobility is intrinsic to the operation of the MESFET and is attributed to an increase in ionized impurity scattering as free electron screening is reduced. P. Lepoivre then discussed the numerical simulation of the effects of the mobility profiles on the microwave response of submicron GaAs MESFETs.

The last talk of the session was presented by D.C. Look (Wright State Univ., US), who described a detailed investigation of characterization of 12 SI GaAs substrates from four different manufacturers by Hall effect, photoluminescence, SSMS, and SIMS techniques. In addition, Se-ion-implanted MESFETs were fabricated on the substrates and tested. Electrical surface type conversion tests were carried out under both VPE-growth and post-implantation-annealing conditions. Studies of some samples that type converted and exhibited an acceptor level at 0.1 eV and a PL band at 1.4 eV indicated that the dominant acceptor concentration far exceeded the measured Mn concentration. It was concluded the Mn is not responsible for the 0.1-eV conversion in all cases, and the existence of a defect at this energy was suggested. The MESFET I-V characteristics indicated that FET mobilities in some cases depended strongly upon the respective mobilities in the virgin substrate materials.

Concluding remarks were by J.P. Hallais (LEP, France). He noted that while the conference was difficult to summarize, it was possible to contrast sharply the "chromium-doped GaAs" conference held in Nottingham 2 years ago with the "stoichiometry of GaAs" conference of Evian. In his view, the story of EL2 is just beginning and is likely to get more complex. He also characterized the prediction of the death of GaAs:Cr heard at the conference as being rather like a weather forecast; while sunshine may be promised, carry your raincoat! Semi-insulating InP is, in its present Fe-doped state, "still looking for its deep center." His answer to the question "can we fabricate GaAs ICs with state-of-the-art material?" was yes, but with continued short-term research and development and long-term research programs still required to reach the ultimate potential of the technology.

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